Spatial Distribution of Extractable Phosphorus, Potassium, and Magnesium as Influenced by Fertilizer and Tall Fescue Endophyte Status

Harry H. Schomberg,* John A. Stuedemann, Alan J. Franzluebbers, and Stanley R. Wilkinson

ABSTRACT

Animals influence nutrient cycling within grazed systems, and the effect may be greater with tall fescue (*Festuca arundinacea* Schreb.) because of endophyte-produced alkaloids that cause fescue toxicosis and alter animal behavior. Twelve grazed tall fescue pastures, established in a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) soil near Watkinsville, GA were used to measure fertility (134–15–56 and 336–37–139 kg N–P–K ha^{-1} yr^{-1}) and endophyte (low, 0 to 29% and high, 65 to 94%) effects on P and K distribution. Soil samples were collected in winter 1997 at distances of 1, 10, 30, 50, and 80 m from permanently located shade and water sources at eight depth increments down to 1.5 m. Nutrient accumulation was greatest 1 m from shade and water sources where P, K, and Mg concentrations were 1.7 to 8, 2.5 to 15, and 1.1 to 1.5 times greater than average concentrations at the remaining distances, depending on depth and fertility level. Accumulation of P, K, and Mg in the area 10 to 80 m from shade and water was limited. When summed for the 0- to 300-mm depth and estimated on a per hectare basis, extractable P was 64% greater in high than in low endophyte-infected tall fescue pastures at 1 m from shade and water sources (703 vs. 428 kg ha^{-1}, LSD = 93) and averaged 252 kg ha^{-1} for remaining distances. Endophyte levels did not affect K distribution and only affected Mg distribution under the low-fertility treatment. Endophyte effects accrued over a long time period, which would indicate that altering grazing and pasture management (movement of animals, fertilizer and lime applications, and location of shade and water sources) to reduce these effects would be needed only occasionally to reduce potential environmental risks.

Animals modify nutrient cycling within grazed systems by significantly influencing nutrient removal and redistribution (Wilkinson and Lowrey, 1973; Mott, 1974; Haynes and Williams, 1993). Sixty to ninety percent of nutrients consumed by grazing animals are recycled back to soil and plants in dung and urine patches, which cover 30 to 40% of the pasture surface annually (Barrow, 1967; Haynes and Williams, 1993). Nutrients in excreta patches are subject to gaseous and leaching losses as well as chemical fixation and immobilization, which together act to reduce nutrient cycling efficiency within grazed systems.

Tall fescue was introduced and widely adopted in humid areas of the eastern USA during the 1940s because of its high yield and persistence (Stuedemann and Hoveland, 1988). Observations of poor animal performance on tall fescue have been directly associated with the alkaloid-producing fungal endophyte *Neotyphodium coenophialum* (Morgan-Jones & W Gams) Glenn, Bacon & Hamlin (syn. *Acremonium coenophialum* Morgan-Jones & Gams) (Stuedemann and Hoveland, 1988). Animals grazing high endophyte-infected fescue have lower levels of intake, daily gain, and heat tolerance than animals grazing low-endophyte fescue. Because of poor heat tolerance, animals grazing high endophyte-infected fescue tend to spend more time in the shade during hot periods of the day, consume more water, and urinate more frequently (Stuedemann et al., 1986). Nutrient redistribution may therefore be related to endophyte effects on animal behavior (West et al., 1989; Wilkinson et al., 1989).

Few studies have investigated nutrient distribution following grazing of endophyte-infected tall fescue. Wilkinson et al. (1989) found two to three times greater K near shade and water sources in high than in low endophyte-infected tall fescue pastures after the first 3 yr. Accumulation was confined to the area within 13.5 m of the shade and water sources. In the same pastures, but after 15 yr grazing, accumulation of soil organic matter was 7% greater in high than in low endophyte-infected tall fescue (Franzluebbers et al., 2000). West et al. (1989) found that after 5 yr of grazing, elevated K and P levels extended 10 to 20 m from watering areas in two tall fescue pastures in southcentral Iowa.

Although not on fescue, Mathews et al. (1994) observed accumulations of N, P, and K near shade and water sources after 2 yr of cattle grazing bermudagrass [*Cynodon dactylon* (L.) Pers.] in Florida. They found no effect on nutrient distribution between rotational and continuous stocking, even though they had expected more even distribution of nutrients under the rotational stocking. In a second study, Mathews et al. (1999) found significant accumulations of N, P, and K within 15 m of shade sources (trees) but no significant accumulation within 15 m of water sources in a Hawaiian kikuyu (*Pennisetum clandestinum* Hochst. ex Chiov.) grassland grazed for 2 yr.

Long-term effects of grazing animals on nutrient redistribution have received limited attention but could be important for site-specific fertilizer recommendations and management changes to reduce effects of animals on nutrient losses through runoff, leaching, and atmospheric transfer from localized accumulation zones. Understanding plant–animal interaction effects on nutrient cycling within the soil–plant–animal system could help improve sustainability. Our objectives were to determine the effects of fertilizer rate and level of endophyte infection on lateral and vertical distribution of soil minerals in long-term (i.e., 8 and 15 yr) grazed tall fescue pastures.

MATERIALS AND METHODS

The study area was in 12 'Kentucky 31' tall fescue pastures established near Watkinsville, GA (33°52′ N, 83°25′ W) on gently sloping Cecil sandy loam soil. Mean annual temperature

USDA-ARS, J. Phil Campbell, Sr., Natural Resources Conservation Center, 1420 Experiment Station Rd., Watkinsville, GA 30677-2373. Received 3 Jan 2000. *Corresponding author (hschomberg@ag.gov).

Published in Agron. J. 92:981–986 (2000).

for the location is 16.5°C, rainfall is 1250 mm, and pan evaporation is 1560 mm. Pastures were 0.7 to 0.8 ha with permanent shade and water sources placed ~20 m apart along one end (a diagram of one paddock is included in Wilkinson et al., 1989). Eight pastures were established in the fall of 1981 and grazing began in the spring of 1983 (15 grazing yr). The pastures were previously described by Wilkinson et al. (1989). These eight pastures composed a two by two factorial experiment with two levels of endophyte infection (low, 29% and high, 65%) and two levels of fertility (low, 134–15–56 and high, 336–37–139 kg N–P–K ha^{-1} yr^{-1}) with two replications. Four additional pastures were established in 1988 and grazing began in 1989 (8 grazing yr). Fertilization levels were the same as in the high-fertility treatment above with two pastures having low (0%) and two having high (94%) endophyte infection. Because the second set of pastures was established 7 yr after the first set, and there was no low-fertility treatment in the second set of pastures, fertility and age were considered a combined effect (fertility–age) in this study. This results in a two factor experimental design, with three levels of fertility–age (high 15 yr; low 15 yr, and high 8 yr) and two levels of endophyte infection (high and low).

Following establishment, pastures were continuously stocked with yearling Angus steers (*Bos taurus*) weighing about 240 kg, with the predominate grazing periods in the spring and fall. A put-and-take system of animal management was used to maintain available forage near 1600 to 1800 kg ha^{-1} in all pastures using variable stocking during animal response measurement periods. Available forage approached 500 kg ha^{-1} at the end of the grazing season. Steer numbers were adjusted biweekly to maintain comparable levels of available forage for all treatments. No forage was removed from the pastures by means other than grazing.

Soil samples were collected on an arc extended around the shade and water sources in each pasture at distances of 1, 10, 30, 50, and 80 m from the shade and water sources during a 3-wk period in late January and early February 1997. At each distance, eight cores (41-mm diam.) separated by ~5 m near the shade and water sources and 8 to 15 m at greater distances were composited within depths of 0 to 25, 25 to 75, 75 to 150, 150 to 300, 300 to 600, 600 to 900, 900 to 1200, and 1200 to 1500 mm. Soil was oven-dried (55°C, 48 h), weighed, and crushed to pass a 4.75-mm screen to partially homogenize the sample and remove stones (<1% of weight). Bulk density was calculated from soil oven-dry weight and volume of the coring device. Soil for mineral analysis was further ground to pass a 2-mm sieve. A 10-g sample was extracted with 40 mL dilute double acid (0.05 *M* HCl + 0.025 *M* H_2SO_4) for determination of extractable K, P, and Mg by inductively coupled plasma spectrophotometric analysis (Plank, 1985). Soil nutrient content for each depth, expressed on a mass per volume basis (g m^{-3}), was calculated from the measured concentration in the soil (g kg^{-1}) and bulk density (kg m^{-3}) of each soil layer.

Endophyte, fertility–age, and animal effects, expressed as nutrient distribution from shade and water sources, were determined using the general linear models (GLM) procedure in SAS (SAS Institute, 1988) and included depth as a repeated measure (Freund et al., 1986). A test for sphericity was used to determine the appropriate univariate or multivariate analysis for the depth effect (Freund et al., 1986). Distance from shade and water sources was treated as a fixed effect. Where significant distance effects were indicated in the repeated measures analysis, regression analysis using distance as a continuous variable was used to determine if distribution of nutrients were different at distances greater than 1 m because of the large accumulations of nutrients at this distance.

A second GLM analysis of endophyte, fertility–age, and distance from shade and water sources effects on whole-profile P, K, and Mg contents was also performed. Whole-profile ion contents (g m^{-2}) were calculated by multiplying concentration (g m^{-3}) times layer thickness (m) for each depth and summing the values (data are presented as kg ha^{-1} or Mg ha^{-1}). As in the previous analysis, distance from shade and water sources was considered a fixed effect but regressions were determined as appropriate. Fisher's least significant difference (LSD) was calculated for comparison of means where *F* statistics were significant at $\alpha < 0.10$ (Ott, 1977).

RESULTS

Depth effects for P, K, and Mg were predominantly limited to the upper 300 mm of the soil profile, therefore data for the lower depths were combined and reported as one depth. The statistical analysis indicated that multivariate results were most appropriate for depth and depth interaction effects. Additionally, because of the limited effects at the greater depths, data reported for the whole profile are for the 0- to 300-mm depth.

Extractable P distribution was influenced by animal behavior as indicated by a large accumulation near the water and shade sources and decreasing concentrations of extractable P as distance from the shade and water sources increased (Fig. 1 and 2, Table 1). This indicates a greater potential for P loss to surface water sources in areas where cattle are allowed free access to streams and ponds. The redistribution of extractable P was influenced by the level of endophyte infection and a fertility–age effect (Table 1). Concentrations of extractable P down to 300 mm were greater at 1 m from shade and water sources than at other distances (Fig. 1 and 2). Below 300 mm, extractable P concentration remained less than 5 g m^{-3} across pastures. At all depths down to 300 mm, extractable P was greater in high than in low endophyte-infected tall fescue pastures at 1 m from the shade and water sources (Fig. 1). A similar endophyte effect was also present for the 0- to 25-mm depth

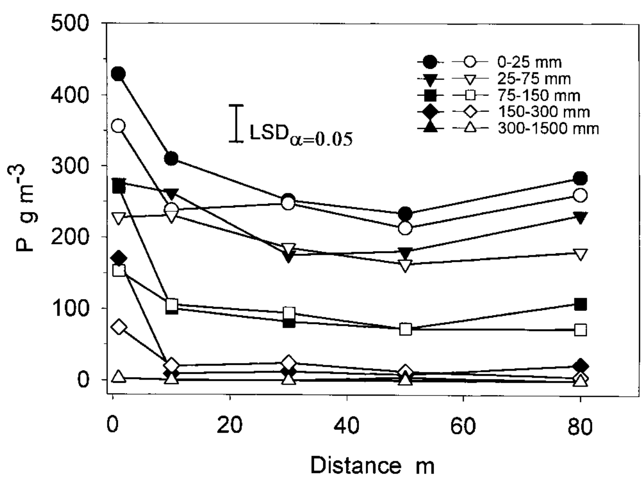

Fig. 1. High (black symbols) and low (open symbols) endophyte infection and distance from shade and water sources effects on distribution of extractable P in grazed tall fescue pastures. The Fisher's least significant difference (LSD) was estimated at $\alpha = 0.05$ using the univariate mean square error term.

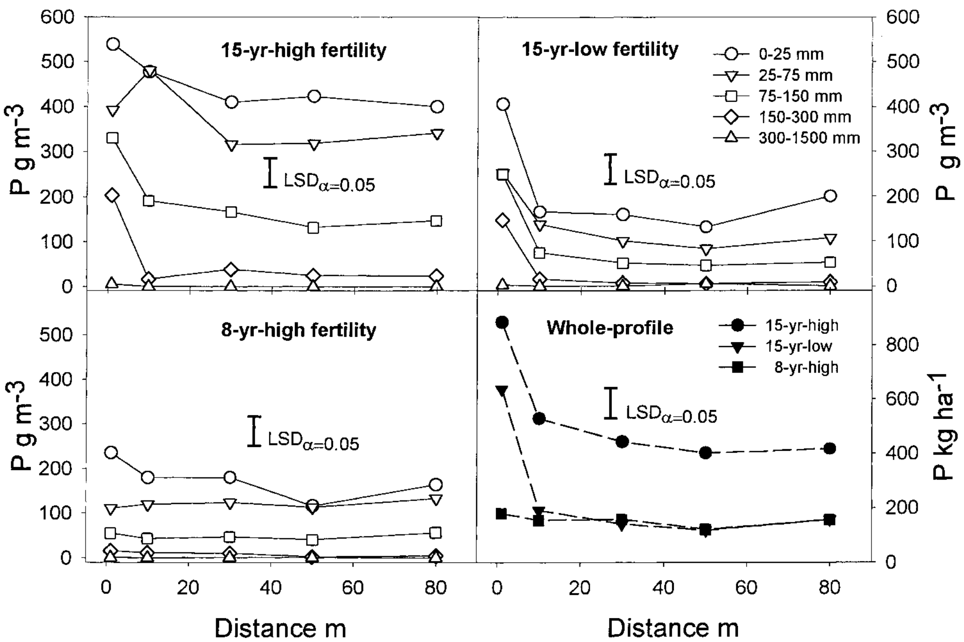

Fig. 2. Fertility–age and distance from shade and water sources effects on distribution of extractable P in grazed tall fescue pastures after 15-yr-high, 15-yr-low, and 8-yr-high fertility within the soil profile (five depths) and for the whole profile (0–300 mm). Note change in *y* axis scale for whole-profile data. Fisher's least significant difference (LSD) was estimated at $\alpha = 0.05$ using the univariate mean square error term.

10 m from the shade and water sources but not at greater depths or distances. When summed for the 0- to 300-mm depth, the content of extractable P was 64% greater in high than in low endophyte-infected tall fescue pastures at 1 m from the shade and water sources (703 vs. 428 kg ha^{-1}, LSD = 93) and averaged 252 kg ha^{-1} for remaining distances.

Extractable P redistribution was more apparent in 15-yr-old than 8-yr-old pastures (Fig. 2, Table 1). After 15 yr, concentrations of extractable P were greater throughout the pasture in the high than in the low-fertility pastures as would be expected, but the effect of cattle congregating near shade and water sources was equally apparent under both fertility regimes (Fig. 2). In 8-yr-old pastures, animal effects were apparent near the surface (0 to 25 mm) and became less apparent at greater depths due to the shorter grazing and fertilization history compared with the 15-yr-old pastures. From 10 to 80 m, P content decreased on average 4.5 kg ha^{-1} m^{-1} in 15-yr-old pastures but changes were not detected in the 8-yr-old pastures beyond 1 m.

Animal influences on extractable K distribution were similar to those for P (Fig. 3, Table 1). However, there was greater movement of K through the soil profile as shown by an accumulation of K in depths below 300 mm at 1 m (Fig. 3). Accumulation of K below 300 mm occurred under both fertility regimes in the 15-yr-old pasture but not in the 8-yr-old pastures receiving the high-fertility treatment (Fig. 3). Extractable K concentrations 1 m from the shade and water sources were 2.5 to 15 times greater than those in the rest of the pasture depending on profile depth and fertility–age. Even with the significant transfer of K deep into the profile, concentrations were greatest at the soil surface across the pasture reflecting deposition, fertilization, attachment to cation exchange sites on clays, and greater surface

Table 1. Analysis of variance results evaluating fertility–age, endophyte, and distance from shade and water sources effects on extractable P and K within the soil profile (depths) and for the whole profile.

		Within profile			Whole profile		
Treatment effect	**df**	**K**	**P**	**Mg**	**K**	**P**	**Mg**
			P > F			P > F	
Fertility–age (F-A)	**2**	**.0001**	**.0001**	**.0001**	**.0001**	**.0001**	**.0015**
Endophyte	**1**	**ns†**	**.0040**	**.0021**	**ns**	**.0026**	**ns**
F-A × endophyte	**2**	**ns**	**ns**	**ns**	**ns**	**ns**	**.0639**
Distance	**4**	**.0001**	**.0001**	**.0001**	**.0001**	**.0001**	**ns**
Distance × F-A	**8**	**.0001**	**.0003**	**ns**	**.0001**	**.0001**	**ns**
Distance × endophyte	**4**	**ns**	**.0236**	**ns**	**ns**	**.0001**	**ns**
Depth	**4**	**.0001**	**.0001**	**.0001**	**na‡**	**na**	**na**
Depth × F-A	**8**	**ns**	**.0001**	**.0001**	**na**	**na**	**na**
Depth × endophyte	**4**	**ns**	**.0559**	**.0753**	**na**	**na**	**na**
Depth × distance	**16**	**.0001**	**.0001**	**.0018**	**na**	**na**	**na**
Depth × F-A × distance	**32**	**.0118**	**.0004**	**ns**	**na**	**na**	**na**
Depth × endophyte × distance	**16**	**ns**	**.0328**	**ns**	**na**	**na**	**na**

† ns equals not significant at P = 0.05.
‡ na equals not applicable.

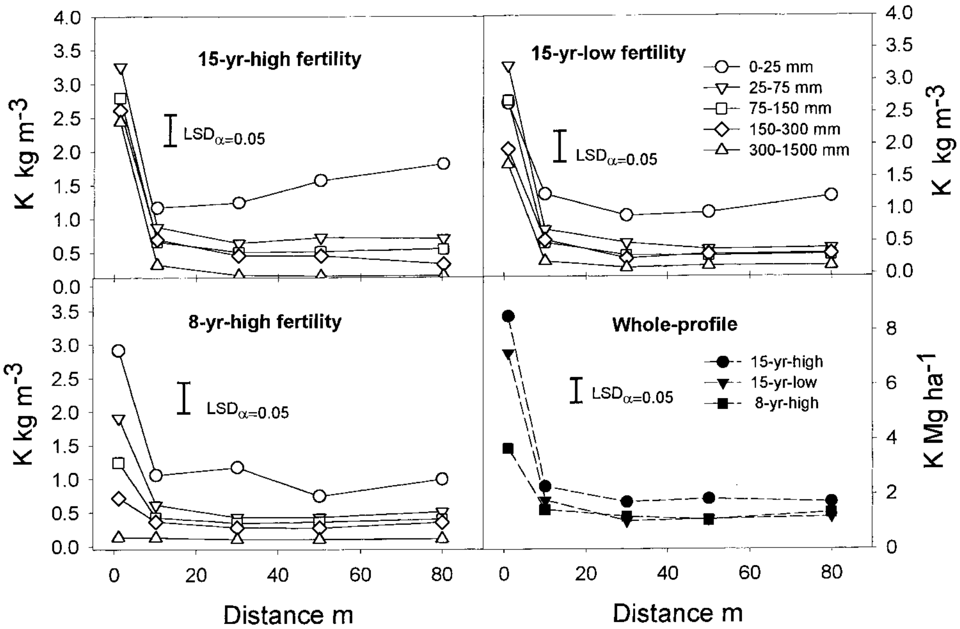

Fig. 3. Fertility–age and distance from shade and water sources effects on distribution of extractable K in grazed tall fescue pastures after 15-yr-high, 15-yr-low and 8-yr-high fertility within the soil profile (five depths) and for the whole profile (0–300 mm). Note change in *y* axis scale for whole-profile data. Fisher's least significant difference (LSD) was estimated at $\alpha = 0.05$ using the univariate mean square error term.

organic matter content. Arifin et al. (1973) found that K fixation in these soils was several times greater than the cation exchange capacity of similar soils, which probably contributed to our observed significant accumulation of K. Extractable K in the 0- to 25-mm depth increased 9.79 kg ha^{-1} m^{-1} from 10 to 80 m in the 15-yr-old pastures (Fig. 3) but no increases were determined for the low-fertility 15-yr-old pasture or the 8-yr-old high-fertility pasture. Even when summed for the 0- to 300-mm depths, only the fertility–age effect was significant (Table 1) with greater K accumulation near the shade and water sources in the 15-yr-old pastures and no difference between the two fertility levels (Fig. 3). In contrast to the results observed with P, endophyte level had no influence on K distribution across grazed pastures or within the soil profile (Table 1). These results are different from those of Wilkinson et al. (1989) and are further discussed below.

Endophyte and fertility management had an effect on Mg distribution within the soil profile and across the grazed pastures (Fig. 4, Table 1). Similar to the results with P and K, there was an accumulation of Mg near the shade and water source (Fig. 4). Concentration of Mg in soil within the various depths was greater in the high than with the low endophyte-infected fescue. This effect was consistent across the distances for the upper three depths (Fig 4). Endophyte infection had no influence on Mg content in the whole profile (0 to 300 mm) of high-fertility 15-yr-old and 8-yr-old pastures (average 5.3 and 4.3 Mg ha^{-1}, respectively) but low-fertility 15-yr-old pastures had greater Mg content in high than in low endophyte-infected fescue soil (5.6 vs. 4.6 Mg ha^{-1}). Although Mg contents for soils in the different treatments were within the range identified as adequate for forage and animal nutrition, these differences in Mg accumulation under different levels of endophyte infection may warrant further study to evaluate the potential longer-term effects on animal performance.

DISCUSSION

Areas near shade and water sources receive the greatest inputs of feces and urine and are therefore subject to greater nutrient accumulation and potential for movement deeper in the soil profile. Soil organic C and N were greater in a zone from 1 to 10 m from shade and water and particulate organic C and N were greater in a zone from 1 to 30 m from shade and water sources compared with farther away in these same pastures (Franzluebbers et al., 1999). Of the three nutrients considered in this study, K and Mg are subject to cation exchange properties of the clays and organic matter, while P sorption to hydrous oxides and reactions with Al and Fe limit mobility. Heavy accumulations of organic matter near the shade and water sources can contribute to ion movement because soluble organic materials block adsorption sites on hydrous oxide surfaces, decreasing phosphate adsorption (Sanchez and Uehara, 1980; Yuan, 1980); sequester nutrients within organic structures; and serve to mobilize nutrients as soluble organic forms. Additionally, in soils with low buffering capacity, increases in pH directly below dung patches can decrease P adsorption and result in movement of P to greater depths (During and Weeda, 1973; Weeda, 1967). Significant stratification of nutrients within the soil profile at areas away from the shade and water sources reflect the stratification of organic matter and clay content of these severely eroded piedmont soils. Organic matter was greatest at the surface and decreased with depth while clay content increased with depth (Franzluebbers et al., 2000). These highly weath-

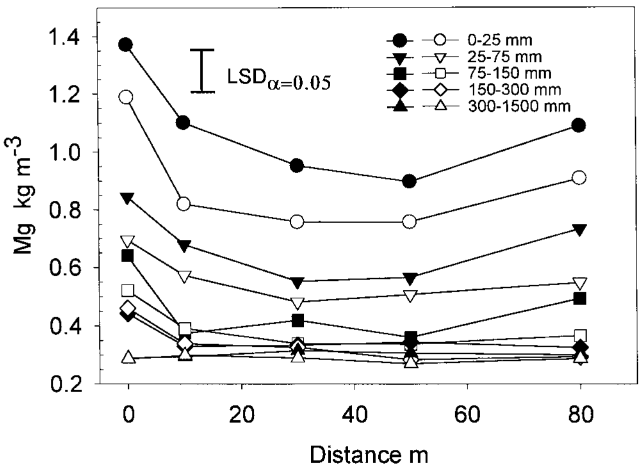

Fig. 4. High (black symbols) and low (open symbols) endophyte-infection and distance from shade and water sources effects on distribution of extractable Mg in grazed tall fescue pastures. The Fisher's least significant difference (LSD) was estimated at α = 0.05 using the univariate mean square error term.

ered kaolinitic soils retained significant quantities of K and Mg and slowed movement of P through the soil profile in areas of concentrated feces and urine inputs.

Results for K distribution across the pasture are similar to those observed by Wilkinson et al. (1989) after 3 yr of grazing in these same pastures (15-yr-old pastures). However, K levels near the shade and water sources are about three to four times greater than those measured in 1986 while concentrations in the remaining pasture approximately doubled. Additionally, Wilkinson et al. (1989) also found a much stronger effect of endophyte and fertility level on the distribution of K. Much of the difference between the two evaluations is attributed to continued inputs of fertilizer and animal behavior effects. However, some of the differences may be attributed to different sampling patterns between the two studies. Our samples were collected at specific distances from the shade and water sources while those of Wilkinson et al. (1989) were collected within 10- to 15-m zones across the pastures. Their sampling pattern may have resulted in a greater dilution of nutrient concentrations because of mixing samples taken near the shade and water sources with samples taken up to 10 m away. Large accumulations of K near the shade and water sources were expected because of the tendency for cattle to congregate in these areas. That the effect was greatly diminished at 10 m was a surprise since significant loafing of cattle and deposition of cattle excreta are observed in this area (Seman et al., 1997). Grazing animals retain only small quantities of K and since plants are heavy accumulators of K, the net effect of grazing is to concentrate K into areas where cattle congregate. The depth of the effect is more surprising but could be attributed to the low cation exchange capacity of kaolinitic clays in these soils, high rainfall (1250 mm yr^{-1}), and the limited vegetation and plant uptake near the shade and water sources due to trampling of vegetation by animals.

Mineral contents for the whole profile were about 5.0 times greater for K, 2.4 times greater for P, and 1.1 times greater for Mg at 1 m from the shade and water sources compared with the remaining pasture. Mineral contents in areas of the pastures away from the shade and water sources were similar, indicating that animal effects were limited to less than 10 m of the shade and water sources. In other studies, concentrations of P and K within 10 m of water sources have been found to exceed by five times those of the remaining pasture after four or five grazing seasons (West et al., 1989; Gerrish et al., 1993) and the zone of influence may extend 30 to 45 m when grazing activity is managed in a similar pattern for more than 20 yr (Gerrish et al., 1993). Excretal deposition patterns are influenced primarily by water, shade, and topography (Haynes and Williams, 1993). Soil properties, clay type, organic matter content, climate, and animal behavior may further moderate the effect. Results from this location indicate that in a soil with predominately kaolinitic clay, effects of animal behavior may occur after 3 yr (Wilkinson et al., 1989) for some nutrients (K) but may take more than 8 yr for other nutrients (P).

Endophyte effects on nutrient cycling and distribution required a longer period of time to detect than animal management effects. Wilkinson (unpublished data, 1986) observed no effect of endophyte level on P or Mg distribution when these pastures were sampled following 3 yr of grazing. We found a greater effect in the 15-yr-old pastures than in the 8-yr-old pastures. In addition, we observed some limited effects of endophyte levels on Ca and Zn distribution that were similar to those observed for P and Mg (unpublished data). Endophyte-infected fescue may result in greater accumulation of some nutrients near the soil surface because of lower grazing pressure. Grazing animals increase the rate of plant residue decomposition and the potential for nutrient losses because of a reduced capacity of the plants to take up nutrients. In nongrazed systems, nutrient cycling rates are more dependent on the slower process of plant residue decomposition (Wedin, 1996) and accumulation of biomass may act as a reservoir of nutrients. The presence of the endophyte causes the gazing animal to be more selective and forage consumption is reduced during certain periods of the year. Thus in the presence of the endophyte, rates of nutrient cycling may be depressed and could be related to slower rates of organic matter decomposition and more continuous periods of vegetation. In contrast, the greater effect of animal behavior on nutrient redistribution appears to result in localized accumulation of nutrients near congregating areas and potential for losses in runoff and leaching.

SUMMARY

Previous studies have shown that excretal deposition patterns are influenced primarily by water, stocking rates, shade, and topography (Haynes and Williams, 1993). We found similar results with P, K, and Mg accumulation at 1 m from the shade and water sources in high and low endophyte-infected tall fescue pastures. Concentrations 1 m from the shade and water sources compared with those in the rest of the pasture were 1.7

to 8.0 times greater for P, 2.5 to 15.0 times greater for K and 1.5 times greater for Mg depending on soil depth. There was little indication of spatial redistribution of minerals in the area 10 to 80 m from the shade and water. This may suggest reduced efficiency of fertilizer use since mineral accumulation was absent in spite of inputs of 555 kg P ha^{-1} (37 kg P yr^{-1}) over the 15-yr period. Potassium accumulation near the shade and water sources was great enough for the effect to extend deep into the soil profile, while with P and Mg the effect was mostly apparent down to 75 mm. Similar distributions within the profile and across distances were observed when considering whole-profile soil contents.

Concentrations of P and Mg were greatest with high endophyte-infection levels for several depths. Endophyte levels also influenced the whole-profile amounts of P and Mg but the magnitude of the effect was moderated by fertility. The indirect influences of endophyte infection on nutrient redistribution become increasingly apparent with time (comparison with observations made by Wilkinson et al., 1989) but pasture management (stocking rate, movement of animals, and fertilizer and lime applications) may mask these effects. Movement of shade and water sources and ensuring that these are not located in areas subject to runoff should increase nutrient use efficiency and reduce the risk of nutrient loss to the environment.

ACKNOWLEDGMENT

Thanks to Robin Woodroof for sample analysis; David Lovell, Johnny Doster, and Jimmie Ellis for help with sample collection and processing; and Fred Hale, Ronald Phillips, and Ned Dawson for pasture management.

REFERENCES

Arifin, N., H.F. Perkins, and K.H. Tan. 1973. Potassium fixation and reconstitution of micaceous structures in soils. Soil Sci. 116:31–35.

Barrow, N.J. 1967. Some aspects of grazing on nutrition of pastures. J. Aust. Inst. Agric. Sci. 33:254–262.

During, C., and W.C. Weeda. 1973. Some effects of cattle dung on soil properties, pasture production, and nutrient uptake. N.Z. J. Agric. Res. 16:423–430.

Franzluebbers, A.J., N. Nazih, J.A. Stuedemann, J.J. Fuhrmann, H.H. Schomberg, and P.G. Hartel. 1999. Soil carbon and nitrogen pools under low- and high-endophyte-infected tall fescue. Soil Sci Soc. Am. J. 63:1687–1694.

Franzluebbers, A.J., J.A. Stuedemann, and H.H. Schomberg. 2000. Spatial distribution of soil biochemical properties under grazed tall fescue. Soil Sci. Soc. Am. J. 64:635–639.

Freund, R.J., R.C. Littell, and P.C. Spector. 1986. SAS for linear models. SAS Institute, Cary, NC.

Gerrish, J.R., J.R. Brown, and P.R. Peterson. 1993. Impact of grazing cattle on distribution of soil minerals. p. 66–70. *In* J.M. Phillips (ed.) Proc. Am. Forage Grassl. Conf., Des Moines, IA. 29–31 Mar. 1993. Am. Forage Grassl. Council, Georgetown, TX.

Haynes, R.J., and P.H. Williams. 1993. Nutrient cycling and soil fertility in the grazed pasture ecosystem. Adv. Agron. 49:119–199.

Mathews, B.W., L.E. Sollenberger, V.D. Nair, and C.R. Staples. 1994. Impact of grazing management on soil nitrogen, phosphorus, potassium, and sulfur distribution. J. Environ. Qual. 23:1006–1013.

Mathews, B.W., J.P. Tritschler, II, J.R. Carpenter, and L.E. Sollenberger. 1999. Soil macronutrient distribution in rotationally stocked Kikuyugrass paddocks with short and long grazing periods. Commun. Soil Sci. Plant Anal. 30:557–571.

Mott, G.O. 1974. Nutrient recycling in pastures. p. 323–339. *In* D.A. Mays (ed). Forage fertilization. ASA, CSSA, and SSSA, Madison, WI.

Ott, L. 1977. An introduction to statistical methods and data analysis. Duxbury Press, North Scituate, MA.

Plank, C.O. 1985. Soil test handbook for Georgia. Georgia Coop. Ext. Serv., Univ. of Georgia, Athens.

Sanchez, P.A., and G. Uehara. 1980. Management considerations for acid soils with high phosphorus fixation capacity. p. 471–514. *In* F.E. Khasawneh et al. (ed.). The role of phosphorus in agriculture. ASA, CSSA, and SSSA, Madison, WI.

SAS Institute. 1988. SAS user's guide: Statistics. 6th ed. SAS Inst., Cary, NC.

Seman, D.H., J.A. Stuedemann, and J.E. Anderson. 1997. Spectral analysis of bovine grazing behavior on *Neotyphodium coenophialum* infested tall fescue. Appl. Animal Behavior Sci. 54:73–87.

Stuedemann, J.A., and C.S. Hoveland. 1988. Fescue endophyte: History and impact on animal agriculture. J. Prod. Agric. 1:39–44.

Stuedemann, J.A., S.R. Wilkinson, D.J. Belesky, C.S. Hoveland, O.J. Devine, F.N. Thompson, H.C. McCampbell, M.E. Townsend, and H. Cioridia. 1986. Effect of level of fungus and nitrogen fertilization rate of KY-31 tall fescue on steer performance. J. Anim. Sci. 63(Suppl. 1):290–291.

Wedin, D.A. 1996. Nutrient cycling in grasslands: An ecologist's perspective. p. 29–44. *In* R.E. Joost and C.A. Roberts (ed). Nutrient cycling in forage systems. Proceedings of a Symp., Columbia, MO. 7–8 Mar. 1996. Potash and Phosphate Inst. and Foundation for Agron. Res., Manhattan, KS.

Weeda, W.C. 1967. The effects of dung patches on pasture growth, botanical composition and pasture utilization. N.Z. J. Agric. Res. 10:150–159.

West, C.P., A.P. Mallarino, W.F. Wedin, and D.B. Marx. 1989. Spatial variability of soil chemical properties in grazed pastures. Soil Sci. Soc. Am. J. 53:784–789.

Wilkinson, S.R., and R.S. Lowrey. 1973. Cycling of mineral nutrients in pasture ecosystems. p. 247–315. *In* G.W. Butler and R.W. Bailey (ed). Chemistry and biochemistry of herbage. Academic Press, London and New York.

Wilkinson, S.R., J.A. Stuedemann, and D.P. Belesky. 1989. Soil potassium distribution in grazed K-31 tall fescue pastures as affected by fertilization and endophytic fungus infection level. Agron. J. 81: 508–512.

Yuan, T.L. 1980. Adsorption of phosphate and water-extractable soil organic material by synthetic aluminum silicates and acid soils. Soil Sci. Soc. Am. J. 44:951–955.